Managing Landslide Risk from Forest Practices in British Columbia

Special Investigation

FPB/SIR/14

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Table of Contents

Executive Summary

Landslides are a common natural process in a mountainous province like British Columbia. The frequency of landslides can be increased by forest harvesting and road building on steep slopes. Usually, landslides are triggered by extreme rainfall events; this was certainly the case in the summer of 1997 when record rainfall over a two-month period in the Salmon Arm area triggered a number of natural and forestry-related landslides. One of these events was a massive debris flow down Hummingbird Creek, near Sicamous, which caused over 3 million dollars damage to public and private property. Hummingbird Creek is a prime example of the damage landslides can cause.

Landslide reduction was one of the major objectives of the 1995 BC Forest Practices Code (the Code). The Code established procedures for professional landslide hazard mapping, site assessment and road engineering procedures to reduce the incidence of landslides associated with forest practices. There is a general assumption that the Code successfully reduced the number of landslides, and that professional assessments were a key part of this success, but to date there has been no evidence to support these assertions.

To address this gap, the Board examined the management of landslide-prone terrain in three areas, two on the Coast and one in the Interior, through evaluation of landslide rates and review of terrain stability mapping and terrain stability assessments. The objectives of this study are to report on:

1. The incidence and trends of forestry-related landslides and the extent of damage to the environment.
2. The adequacy of terrain stability mapping and assessments.
3. The lessons learned in applying this information to the *Forest and Range Practices Act* (FRPA) environment.

How the Study was Done

Airphoto and satellite imagery was used to examine landslide occurrence in Code cutblocks and roads from two areas on Vancouver Island (Kyuquot and Gordon River) and one area in the BC interior (Revelstoke). The terrain stability map hazard rating and the terrain stability field assessment (TSFA) for each cutblock were compared to operational planning documents and to actual landslide occurrence. The comprehensiveness of the TSFA reports was assessed.

Incidence and Trends

A total of 46 Code road and cutblock landslides were counted in the 455 steep slope cutblocks in the three study areas, or an average of one landslide every year for every 14 square kilometres of steep slope cutblocks. This landslide frequency is a significant improvement over pre-Code landslide activity, but is still an increase over natural landslide rates.

There is a significant probability that any landslide that does occur will have an environmental effect. Approximately 60 percent of the Code landslides in the study area had a potential "material adverse effect on a forest value," based on criteria established by the Board, such as defined impacts on a fish stream, loss of soil, or loss of plantation.

Code landslides are not, however, a significant soil conservation issue at the landscape scale, disturbing only 0.3 percent of the total cutblock area. Provincially this figure will be much lower, as the study areas are three of the most landslide-prone areas of the province.

Code landslides differ from pre-Code landslides. Code landslides are much less frequent in gullies, along stream escarpments and off roads, compared to pre-Code landslides. This probably reflects the retention of reserves and management zones around streams and gullies, as well as better road location, and improved construction practices under the Code.

The factors that contributed to the landslides are difficult to determine; in over half the cutblocks examined in this study, the factors could not be determined. Of the remainder, harvesting or road-building on identified high hazard areas, or windthrow in adjacent areas, are the most common contributing factors.

Many more landslides (164 over the eight-year study period) initiated from old roads constructed prior to the Code coming into effect. This is in spite of considerable road deactivation work. While deactivation of pre-Code roads has not been particularly effective in restoring hillslope stability, deactivation appears to effectively stabilize roads built under the Code.

Adequacy of Terrain Stability Mapping and Assessments

Licensees achieved reduced landslide frequencies in the Code era through a number of measures, including better road locations, improved road-building techniques, reserves around stream escarpments and gullies, proactive deactivation, and increased use of professional engineers and geoscientists. The significance of professional terrain mapping and assessments in this equation is the subject of the second part of this report.

Reconnaissance terrain stability mapping, prepared by professional geoscientists, correctly identified most cutblock areas that eventually experienced landslides as potentially unstable or unstable. No landslide cutblocks were mapped as stable. The criteria used for determining landslide hazard class were not always consistent, however, between mappers in the same region. Reconnaissance terrain stability mapping did not appear to be used strategically in planning the location of cutblocks and roads, but rather was used only for determining whether a terrain stability field assessment (TSFA) was needed.

A TSFA was carried out on 92 percent of the cutblocks where required. However, the results of the TSFA were not always incorporated into the silviculture prescription, as is required. About 45 percent of silviculture prescriptions did not address the results of the TSFA; nor were the results of the TSFA addressed in the cutting permit or road layout and design documents. This means that while TSFAs were nearly always being completed where required, in nearly half the cases, the results appear to have been ignored.

Part of the reason for this may have been the utility of the TSFAs themselves. The comprehensiveness of TSFAs examined in this study was quite variable. All TSFAs provided an estimate of the likelihood of a landslide occurrence for the cutblock. Overall, the TSFAs accurately predicted a moderate or high likelihood of a landslide in those cutblocks where they occurred. However, half did not stratify the block by hazard class, provide hazard assessments for adjacent areas, or estimate the size, the number or the consequence of the landslides. Some TSFAs provided detailed prescriptions for block adjustment or road construction, while others were silent. The more recent TSFAs were generally the most comprehensive.

Implications for Landslide Management under FRPA

The system for management of unstable terrain established under the Code seems to work—the incidence of landslides has been reduced. More thorough professional assessments and more consistent implementation of their recommendations should reduce landslide incidence even further. The challenge for landslide management under FRPA is to maintain this momentum. The mandatory aspects of landslide management no longer exist under FRPA, and licensees will now have the discretion to decide when and where to conduct mapping and assessments. The shift from a hazard prevention strategy to a risk management strategy is a significant change from what existed under the Code. The consequence of landslides has now entered the equation and forest managers will have to apply landslide risk management to balance environmental and timber supply objectives.

Six recommendations for implementation of a landslide management system under FRPA are made as a result of this study:

1. The landslide management system that was developed under the Code should continue under FRPA. Terrain stability field assessments can be a strong tool for management of unstable terrain. Licensees should continue doing terrain stability field assessments and use the results.

2. The Ministry of Forests and Range regional offices should establish quantitative criteria for classifying landslide hazard in terrain mapping. A landslide hazard class should be defined by the probability or expected frequency of landslides per unit area, rather than by a subjective description.

3. The Ministries of Environment and Forests and Range should establish what "a material adverse effect" from landslides would be for each resource value in FRPA—with public resources it is the role of government, not individual licensees, to define where the threshold is for a material adverse effect on resource values. It is important to develop criteria for acceptable risk for each of the FRPA values separately.

4. The Ministry of Forests and Range should regularly conduct inventories of landslides as part of the Forest and Range Evaluation Program, as there is no FRPA requirement for licensees to report landslides.

5. Licensees should use a decision-making framework for the management of landslide risk. A framework separates the process of landslide risk management into distinct steps, and clarifies the respective roles of terrain stability professionals and forest resource managers (see the Board's Reiseter Creek complaint investigation for more discussion of this concept). Licensees should also develop objective criteria for triggering when a TSFA must be conducted, to provide consistency in application across their operations. One example is the criteria currently being developed by a coastal licensee that combines terrain stability mapping, climatic zone mapping and watershed use to trigger when a TSFA is needed.

6. The Joint Practices Board, or the ABCFP, should develop companion guidelines for forestry managers to the APEGBC *Guidelines for Terrain Stability Assessments in the Forest Sector*. This guidebook should provide advice to the forest manager in applying appropriate levels of landslide risk management. The guidebook should also provide standardized terminology for effective communication, and clarify the responsibilities of forest managers and terrain professionals.

Introduction and Objectives

Landslides are a common natural process in a mountainous province like British Columbia. Common features of the landscape are steep slopes, gullies, incised streams and shallow soils, which are conducive to landslides. Most of BC's mountainous areas also experience high seasonal precipitation and periods of intense rainfall. Landslides are, consequently, a common natural process. Natural landslides are an important forest disturbance agent, particularly in coastal areas. Landslides in forests create gaps and tree diversity as well as contributing significant amounts of gravel and large woody debris to streams, which are important attributes of fish habitat.

Timber harvesting and road building can increase landslide rates significantly. Increases of 10 to 35 times over natural rates have been documented following logging. These rates of increase were observed in the 1970s in the Queen Charlotte Islands (Rood, 1984; Schwab, 1988) as well as other areas in western North America. Increases of this magnitude can adversely affect stream morphology, fish habitat, water quality, and fish egg and fry survival (Hogan et al, 1998). Landslides can also endanger human life and property, and damage soil and visual resources.

Landslide occurrence, both natural and forest development related, is strongly influenced by climate—landslides are most abundant on the outer West Coast and are much less common in the drier Interior climate regions. The Ministry of Forests has done a number of studies on landslides following forest development. These studies have shown landslide frequencies ranging from 1 Ls/km^2/y (per area of clearcut) on the Queen Charlotte Islands (Rollerson et al, 2001) to 1 Ls/ 60 km^2/y in the West Kootenay area (Jordan, 2002).

Landslide occurrence is, at least in part, dependent on slope. Most slopes steeper than 35 degrees (70 percent) are potentially subject to landslides. Landslide hazard is affected by many factors other than slope, such as depth and texture of glacial deposits, drainage conditions, and type of bedrock. Terrain stability mapping is therefore used to map the susceptibility to landslides of areas proposed for forest development (Chatwin et al, 1990).

On the Coast, many landslides occur in clearcuts, often as a result of root decay following logging. Such landslides typically occur 5-15 years after logging (Chatwin et al, 1990).

In the Interior, relatively few landslides occur as a result of clearcutting (Jordan, 2001). Most landslides related to forest development are caused by roads or skid trails. These landslides are often the result of drainage diversions, and may occur some distance below the road or cutblock.

Landslide reduction became one of the major objectives of the 1995 BC Forest Practices Code (the Code). The Code established procedures for professional landslide hazard mapping, site assessment, and road engineering procedures, to reduce the incidence of landslides. There is a general assumption that the Code reduced the number of landslides, but there is no empirical evidence to support this assertion. Under the recent *Forest and Range Practices Act* (FRPA), which replaces the Code, the assessments and professional oversight are now at the discretion of forest licensees.

Of interest to the public in all this is whether forest practices are still causing landslides on forestlands in BC; what environmental impact are they having; and are practices improving? Licensees and professionals are also interested in whether terrain stability hazard mapping and terrain stability field assessments, carried out by professionals, accurately predict and characterize landslides. That is, are the assessments reliable and useful? Also, where landslides have damaged the environment, where has the management system failed? As we implement FRPA, terrain stability management presents an interesting test case of the faith the public and industry can place on professional reliance.

Therefore the objectives of this study are to report on:

- the incidence and trends of forestry-related landslides in selected areas and the extent of damage to the environment;
- the adequacy of the terrain mapping and assessments; and
- the lessons learned in applying this information to the FRPA environment.

Managing Landslides Under The Code

The Code's *Operational Planning Regulation*, *Forest Road Regulation* and *Timber Harvesting and Silviculture Practices Regulation* specified the requirements for managing landslide-prone terrain. The specific regulations are listed in Figure 1. The regulations describe the terrain stability mapping requirements for forest development plans, the requirements for conducting terrain stability field assessments on proposed cutblocks and roads, the restrictions on harvesting areas with a high likelihood of a landslide, the requirement for silviculture prescriptions to be consistent with the assessments, and the requirement for professionals to conduct terrain stability field assessments and evaluate road building techniques on unstable sites.

The primary method of predicting the likelihood of landslides is to carry out geologic investigations of areas proposed for harvesting and make judgment-based assessments of the likelihood of post-harvest or road construction related landslides. These investigations, referred to as terrain stability field assessments (TSFAs), are used to modify and adjust preliminary harvesting and road construction plans to reduce the potential for landslide activity.

The *Mapping and Assessing Terrain Stability Guidebook* (MOF, 1995/1998) outlines a standard of practice for TSFAs. This guidebook prescribed the expected content and procedures for carrying out assessments. It was a mandatory guidebook under the Code, cited in the *Operational Planning Regulation*.

Figure 1: Regulatory requirements for managing unstable terrain

Mapping requirements for the forest development plan

A forest development plan must include the following information for the area under the plan:

a) areas mapped on terrain stability hazard maps as having a moderate or high likelihood of landslides,
b) areas identified on reconnaissance terrain stability maps as having unstable or potentially unstable terrain, or
c) if no mapping has been carried out, areas with a slope gradient greater than 60%.

Site assessment requirements for the forest development plan

A terrain stability field assessment must be completed…if the area is identified in the forest development plan as having:

a) a high likelihood of landslides
b) unstable terrain, or
c) a slope gradient greater than 60%

Assessments in community watersheds for the forest development plan

In community watersheds, a terrain stability field assessment (TSFA) must be completed for the cutblock if the area is identified in the forest development plan as having:

a) a moderate or high likelihood of landslides
b) unstable or potentially unstable terrain
c) a slope gradient greater than 60%

These additional assessments in community watershed are not required if the area has a moderate likelihood of landslides, is located in the Interior, will be cable harvested and no excavated trails constructed.

Assessments required for Silviculture Prescriptions

A person preparing a silviculture prescription must carry out a terrain stability field assessment …for a cutblock that is located in an area identified in the forest development plan as having a moderate likelihood of landslides or potentially unstable terrain…or in areas where indicators of slope instability are identified while carrying out fieldwork…

The silviculture prescription must contain a statement that the silviculture prescription is consistent with the results or recommendations of the terrain stability field assessment.

Harvesting on areas with a high likelihood of a landslide

A person must not clearcut an area, if a TSFA indicates that the area has a high likelihood of landslides, unless the assessor documents in the TSFA that he has reasonable grounds to believe that clearcutting the area will not significantly increase the risk of a landslide and that there is a low likelihood of landslide debris entering a fish stream or a tributary to a fish stream or causing damage to property or utilities.

Road location and design

…if a person carries out road construction, modification or deactivation, the person must carry out a terrain stability field assessment if the area has:

a) a moderate or high likelihood of landslides, based on terrain stability hazard maps,
b) unstable or potentially unstable terrain based on reconnaissance maps, or
c) slopes greater than 60%, if no mapping has taken place….

…a terrain stability field assessment must be prepared by a qualified registered professional.

A qualified registered professional must sign and seal a statement that the assessments have been carried out and that the road layout and design is consistent with the results and recommendations of the assessment.

Methodology

The study used a risk-based sampling approach. Areas known to have a high likelihood of landslides, based on topography and precipitation, were chosen for study. Two areas on Vancouver Island (Kyuquot and Gordon River) and one area in the BC Interior (Revelstoke) were selected (Figure 2).The reasons for choosing these areas were to capture a significant sample of landslides for analysis, and so that conclusions on the effectiveness of practices can be safely extrapolated to lower-risk sites across the province. These areas were also selected on the basis of the availability of recent (2002-2004) and circa 1995 aerial photography or satellite imagery. Each study area also had a mix of administrative zones (timber supply areas and tree farm licences), licensees and terrain consultants.

Figure 2: Study areas

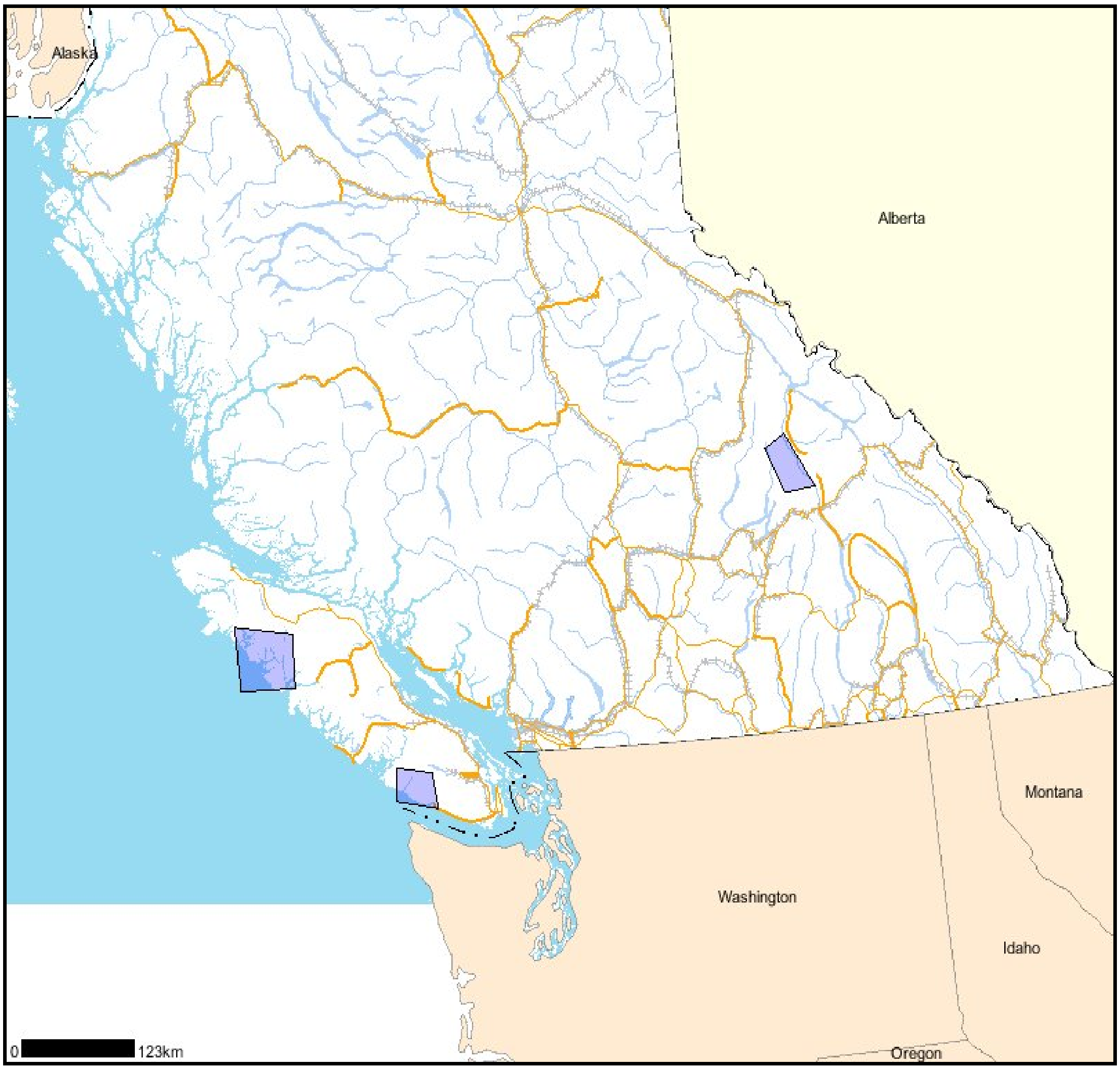


Table 1: Number of cutblocks in each study area

Study area	Total land area surveyed (ha)	Number of steep slope cutblocks*
Gordon River	94,500	262
Kyuquot	198,000	92
Revel stoke	112,000	203

* a steep slope cutblock is a cutblock with an average slope greater than approximately 60 percent

An inventory was made of all landslides visible on the air photos and satellite imagery (see Appendix 1) within the selected harvest areas and the immediately adjacent forested terrain. Landslides from both roads and harvested areas within the area of the cutblock, as well as landslides in adjacent areas that appeared to be a result of harvesting in the cutblock (for example, windthrow edges), were mapped. All natural landslides (not associated with any harvest activity) that occurred during the period 1995-2003, and were within the estimated timber harvest landbase, were also counted. Each landslide was classified as either:

- Post 1995, from a Code cutblock or in-block road,
- Post 1995, from a pre-Code cutblock or in-block road,
- Post 1995, from an unlogged forested area, or
- Pre-1995.

The post-Code cutblocks were recognized by the lack of appreciable green-up on the photos and the date of harvest was confirmed as post-1995 using the map-based data in RESULTS, the provincial electronic database of silviculture records. Road landslides were only counted if they were in-block, as it was very difficult to date roads that were not associated with a specific cutblock.

A set of data was recorded for each landslide that occurred in the harvested areas. Data included the area of the landslide, the initiation point (e.g., open slope, gully, road, windthrow boundary, etc.), and the effect of the landslide on forest values (e.g., did it directly enter a likely fish bearing stream?).

After the landslides were mapped, any terrain stability maps, forest cover maps, logging plan maps, landslide records and TSFA reports for the unstable cutblocks were obtained. The terrain stability map classifications and the results of the TSFA for each cutblock were tabulated. Comparisons were made between the landslide data and the terrain stability mapping and TSFA data. The total number of landslides occurring in each terrain stability map class and each TSFA landslide hazard class was summarized.

In addition to cutblocks that experienced landslides, a sample of 100 cutblocks that had no landslide activity, but because of terrain hazard mapping should have had a TSFA completed, were randomly selected. Compliance with the requirement for a TSFA was determined.

The overall quality of the TSFA reports was measured against a checklist developed from the guidebooks (Table 7). The accuracy with which the TSFAs have predicted slope stability was summarized.

Results

Before discussing the outcome of this survey, an important limitation of the results must be understood. This study examined cutblocks and roads that have been developed since the Code came into effect in 1995. The oldest cutblocks are therefore eight years old and the average age is five years. However, most post-harvest landslides occur 5-15 years or longer, after logging, due to the length of time it takes for root strength deterioration and for a storm of sufficient magnitude to trigger landslides to occur. Road-related landslides can take even longer to occur.

A major storm (a 25-year event) occurred over all three study areas in 1999. This storm likely provided a trigger mechanism for any latent stability problems, causing numerous landslides. Despite this event, the cutblocks and roads examined may just be entering the most susceptible time period; more landslides may occur. This survey must be viewed as preliminary results and a follow-up study is warranted in another 10 years.

Another caveat is that the landslide rate has not been adjusted to take into account the area of pre-Code cutblocks and roads, compared to the area of Code cutblocks and roads. The numbers then indicate general trends, but cannot be taken as numerical comparisons.

A final comment on the data is that the incidence of natural landslides is underestimated by airphoto surveys. It is difficult to see small landslides on airphotos where there is a forest cover, and the majority of landslides are small (Figure 3). Rollerson (personal communication) has documented the inaccuracies in counting small landslides in forested terrain.

Incidence of Landslides

1. ***Are landslides occurring from cutblocks and in-block roads since the Code came into effect?***

A total of 46 road and clearcut landslides, in cutblocks logged under the Code, were inventoried in the three study areas. These landslides occurred in a sample of 557 steep slope cutblocks (slope gradients averaged over 60 percent) with a total cutblock area of 8,310 hectares, scattered over a total land area of 404,500 hectares, in the three study areas. The number of landslides in each study area ranged from a low of 1 landslide every 21 cutblocks to a high of 1 landslide every 5 cutblocks. On average there was 1 landslide every 12 cutblocks. This is equivalent to roughly 1 landslide for every 180 hectares harvested over the eight-year period of the study. On an annual basis, there is 1 landslide/ 14 square kilometres of cutblock/year.

This rate of landslide activity is low. It is, however, 2-3 times greater than the rate of natural landslides reported from forested unlogged watersheds on the West Coast of Vancouver Island (Guthrie, 2002). A precise frequency of natural landslides can't be determined by the airphoto survey method, because counts of small landslides (less than .25 hectares) are severely underestimated because of the obscuring forest cover. A comparison of the frequencies of only the larger size classes of natural and Code landslides (greater than .5 hectares) indicates approximately a fivefold increase.

Table 2: Landslide density in the study areas

Area	Number of cutblocks	Land area surveyed	Number of harvest-related landslides	Landslide density 1 landslide/ # cutblocks	Landslide frequency 1 landslide/ year/# km2
Gordon River	262	94,500	12	21	28
Kyuquot	92	198,000	16	6	10
Revelstoke	203	112,000	18	11	13
Total	**557**	**404,500**	**46**	**12**	**14**

There is still significant ongoing landslide activity from roads constructed pre-Code, in particular from roads built in the 1970s and 1980s (Table 3). In the Gordon River study area, for example, 12 landslides occurred in 262 post-Code cutblocks; however there were 115 landslides that started at old roads in cutblocks logged prior to the Code. Further review is required to determine if the same trends occur over time in the Code landslide rates.

The landslide numbers in Table 2 and Table 3 cannot be used to compare pre-Code and Code landslide rates. There were more pre-Code than Code cutblocks and the data has not been analyzed to reflect that. Also, many landslides in the pre-Code cutblocks occurred prior to 1995 and so were not counted. The point of Table 3 is to illustrate that even in the Code era, landslides are still initiating from pre-Code roads and cutblocks and their number exceeds those initiating in Code cutblocks.

Table 3: Number of landslides from pre-Code cutblocks

Area	Landslides from pre-Code cutblocks (logged 1980-1995), that occurred after 1995	
	landslides	*landslides/year*
Gordon River	115	15
Kyuquot	39	5
Revel stoke	10	1

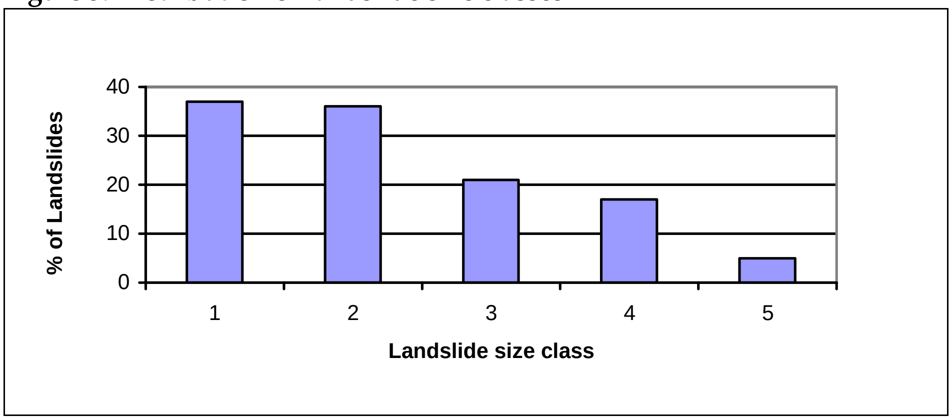
2. *Is the area disturbed by Code landslides a soil conservation concern?*

In order to determine the total area of soil disturbance by landslides, the landslides were classified into the following size classes:

Class	Area (ha)	Description
1	.05 – 0.1	Very small
2	0.1 – 0.25	Small
3	.25 – 0.5	Medium
4	0.5 – 1.0	Large
5	> 1ha	Very large

Figure 3 illustrates the distribution of the Code landslide size classes. Small and very small landslides make up 76 percent of the total, while very large landslides are only 5 percent of the total number of landslides.

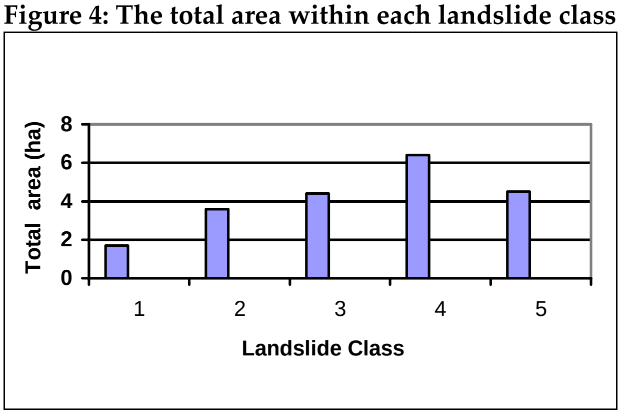
Figure 3: Distribution of landslide size classes



Individual landslides can occupy a significant portion of an individual cutblock. In the group of 46 cutblocks with landslides, landslide-related disturbance ranged from less than 1 percent to a maximum of 12 percent of the cutblock area.

At the landscape level, soil disturbance is a minor concern; landslides occupy only a very small portion of the total cutblock area.

Figure 4: The total area within each landslide class



The total area disturbed in each Code landslide class generally increases as the landslide size class increases (Figure 4). While there are many more very small landslides than larger landslides, the cumulative area disturbed by very small landslides is only 1.7 hectares in the three study areas. The cumulative area of very large landslides is 4.5 hectares. The total area of all size classes of landslides is 21 hectares, out of a total cutblock area of 8,310 hectares. This is only 0.3 percent of the total area of all the cutblocks sampled (by comparison, the allowable limit for permanent roads is 7 percent of the cutblock area).

At the cutblock level, the number of cutblocks with levels of soil disturbance due to landslides is relatively small. At the landscape level, the total area disturbed by Code landslides is a relatively minor concern.

3. *What are the characteristics of the landslides?*

The following characteristics were recorded for each of the inventoried landslides:

- land use at the landslide initiation point: road, clearcut or forest edge
- failure initiation: open slope, gully or stream escarpment
- landslide terminus: open slope, gully, tributary stream or road
- landslide length: length in metres
- landslide area in hectares

The characteristics of cutblocks that had been logged prior to the Code, and cutblocks that had been logged under the Code, were compared by the proportion of all the landslides that fell into each category (comparisons were also made between the Revelstoke and the Vancouver Island populations, but landslide characteristics were not that different).

Table 4: Percentage of landslides in each category

	Landuse			**Failure Point**			**Terminus**			
	Road	*Clearcut*	*Edge*	*Slope*	*Gully*	*Escarp*	*Slope*	*Gully*	*Stream*	*Road*
Pre-Code	80	15	5	39	41	20	18	52	15	15
Post Code	26	44	30	70	19	11	42	34	11	15

	Length (m)					**Area Class**			
	<100	*1-200*	*2-400*	*4-600*	*>600*	*1*	*2*	*3*	*4*
Pre-Code	40	35	10	10	5	30	30	14	25
Post Code	60	25	5	5	5	30	30	20	20

The pre-Code landslides typically originate at roads, occur in gullies and on stream escarpments, terminate in gullies and streams, and are predominately less than 200 metres long and less than 0.25 hectares in area.

By contrast, most Code landslides occur more frequently in clearcuts and on open slopes. Code landslides do not occur as frequently in gullies, do not initiate as frequently from roads, and terminate more frequently on open slopes, and somewhat less frequently in streams. The length and area classes are similar for pre-Code and Code landslides.

One of the reasons for the shift in the character (and possibly the number) of Code landslides is that gullies are logged less frequently, and stream escarpments are not logged anymore. Riparian reserves now extend to the top of stream escarpments and harvesting in gullies is restricted by the gully assessment procedure. The frequency of landslides along roads has also decreased, probably due to some combination of better locations and improved construction methods.

4. Are the landslides having a material adverse effect on forest resources?

The landslides that occurred in Code cutblocks were assessed to determine whether they could be expected to have a "material adverse effect on a forest resource" (this term comes from FPRA). The evaluation was done by examination of airphotos. As most landslides occurred a number of years ago, it was not practical to examine the actual impacts in the field.

FRPA does not define what is meant by "material adverse effect on a forest resource." As a result, the Board had to develop its own criteria to judge what might constitute a potential material adverse effect, for the purposes of this analysis. Landslides were judged to have exceeded the material adverse effect threshold if they had the following characteristics:

- A landslide of 200 cubic metres of sediment or more that directly entered a community watershed stream, a fish-bearing reach of a stream, or a direct tributary of a fish stream within 500 metres of fish habitat.
- A landslide of any size that caused a debris flow that scoured a portion of a fish stream.
- A landslide that delivered in excess of 500 cubic metres of sediment to a stream directly tributary to a fish stream.
- A landslide that destroyed more than 0.25 hectares of forest or plantation.

Table 5: Landslides that may have had a material adverse effect

Impact	Number of landslides*	
More than 200 cubic metres into a fish stream or community watershed stream	Kyuquot	0
	Gordon	5
	Revelstoke	0
Debris flow into a fish stream	Kyuquot	2
	Gordon	3
	Revelstoke	1
More than 500 cubic metres into a stream tributary to a fish stream	Kyuquot	2
	Gordon	4
	Revelstoke	3
More than 0.25 hectares of forest or plantation	Kyuquot	5
	Gordon	4
	Revelstoke	5

*some landslides have a double impact and are counted twice

The criteria used in this study are not necessarily those that will constitute a "material adverse effect" in future determinations. The criteria are an evaluation of the potential consequences to an element, and do not include, for example, an assessment of the actual damage to fish habitat. Also, these criteria do not include an evaluation of the vulnerability or the "worth" of the element. Our criteria are, therefore, used as a 'partial risk' assessment.

A total of 28 landslides in the three study areas met at least one of these criteria (Table 5). While the total number of landslides was low (46), the likelihood of those landslides having a material adverse effect is quite high (60 percent). These landslides occurred over a 10-year period in a population of 561 cutblocks. While there is no standard to judge, an average of one significant resource-damaging landslide per year per study area seems like a reasonable level of achievement.

Figure 5: Airphoto of landslide initiating in a clearcut, crossing a road and depositing into a stream

5. *Has road deactivation been effective in reducing landslide hazard?*

Deactivation is a requirement for Code roads that will not be maintained. Deactivation of logging roads stabilizes the site and reduces erosion. Temporary deactivation removes culverts and installs cross ditches. Permanent deactivation also includes pull back of potentially unstable fills, and planting and seeding of exposed soils. Furthermore, permanent deactivation of roads on slopes with a high likelihood of landslides must be prescribed and signed off by a professional engineer or professional geoscientist.

However, many roads constructed pre-Code were not deactivated when they were no longer in active use. Hundreds of landslides occurred along these 'abandoned' roads over the years. Recognizing the serious impact, the Forest Renewal BC Watershed Restoration Program invested millions of dollars deactivating potentially unstable pre-Code logging roads. Work carried out under this program was not regulated by the Code.

Our survey indicates that deactivation reduces the incidence of landslides on both Code and pre-Code roads, but is less effective on the pre-Code roads. The majority of landslides from pre-Code roads occurred along roads that had not been permanently deactivated (Table 6). However, a significant number of landslides also occurred along deactivated pre-Code roads. The landside counts are evidence that deactivation techniques, as practiced, did not always restore the stability of the site along old roads. Neither, however, does deactivation, as practiced, bring old roads up to the stability standard of non-deactivated Code roads. While non-deactivated pre-Code roads have the highest landslide frequencies, deactivated pre-Code roads also had significantly more landslides than similar natural slopes or roads developed to Code standards (Table 6).

Six landslides occurred along Code roads that had either not been deactivated or had been only temporarily deactivated. One landslide occurred on a fully and permanently deactivated Code road (with fillslopes pulled back, cross–ditching completed, etc.).

Table 6: Landslides from deactivated and non-deactivated roads

Area	Non-deactivated pre-Code roads	Deactivated pre-Code roads	Non-deactivated Code roads	Deactivated Code roads
Gordon	78	16	2	1
Kyuquot	24	8	4	0

Adequacy of Terrain Mapping and Assessments

6. Have TSFAs been completed on all cutblocks and roads, where required by the Code?

A TSFA is required on cutblocks mapped as having a high likelihood of landslides (Class V) or a moderate likelihood of landslides (Class IV) or as being unstable (class U) or potentially unstable (class P), or, in the absence of mapping, a TSFA is also required where slopes are greater than 60 percent. An exemption is allowed for cutblocks located in the Interior that are mapped as Class IV and will be cable harvested. The silviculture prescription (SP) must incorporate the results of a TSFA.

Of the 46 Code cutblocks with landslides, seven Interior blocks did not require a TSFA because they were exempted. Thirty-six of the remaining 39 cutblocks had TSFAs. Three cutblocks (8 percent) did not have a TSFA, even though it was required. No reasons were provided in the SPs for not completing a TSFA on the required cutblocks.

The SPs for all Code cutblocks that experienced landslides were also examined to determine if the conclusions of the TSFA had been incorporated into the SP. Twenty-two SPs (55 percent) indicated that a TSFA had been completed, while the rest did not.

Data from the two study areas (Kyuquot and Revelstoke) with reconnaissance-level terrain stability maps were pooled to examine if SPs incorporated the results of the TSFA for cutblocks mapped as containing the most hazardous terrain: U (unstable) or Class V (high likelihood of a landslide). Thirteen out of a total of 16 SPs (80 percent) reported completed TSFAs.

In addition, a random sample of 100 SPs for cutblocks that did not subsequently experience landslides, but that met the criteria for requiring a TSFA, were reviewed for the three study areas. Of the 100 SPs reviewed, 62 documented that a TSFA was completed.

The conclusion from this analysis is that the compliance with the regulation requiring TSFAs is good (92 percent), however the results from the TSFAs are not always incorporated into the SPs. It is possible that, due to poor record keeping, the results of the TSFA were not included in the SP, or that the TSFA and the SP were contracted at the same time and the results were unavailable for inclusion in the SP. Nevertheless it does indicate a common non-compliance and a breakdown in implementation of assessment results.

7. Do terrain stability maps accurately portray stability conditions? Are terrain stability maps used to avoid unstable areas?

Reconnaissance terrain stability maps were completed for the Revelstoke and Kyuquot study areas at survey intensity level D and E (airphoto mapping, with limited ground truthing) in 1995. These maps were therefore available for planning the location of cutblocks and roads throughout the time-period of the Code.

The record of reconnaissance terrain stability mapping in predicting future landslide occurrence is mixed. In the Revelstoke study area, there were 18 Code cutblocks with landslides and the terrain stability mapping identified 7 of these cutblocks as unstable, 8 as potentially unstable, and 3 as stable. The mapping of 43 steep, but stable, cutblocks was examined in the Kyuquot study area. Reconnaissance terrain stability mapping identified 42 of these cutblocks as potentially unstable and 1 cutblock as stable. Examining only the cutblocks where landslides occurred in Kyuquot, 90 percent were mapped as unstable or potentially unstable and 10 percent were mapped as stable.

It was difficult to determine whether these terrain stability maps were being used to direct cutblock location. With a significant number of areas mapped as class U logged, there is certainly evidence that, with the exception of gullies and stream escarpments, the terrain stability maps are not used for strategic placement of cutblocks and roads. Rather, it appears that reconnaissance terrain stability maps are used mainly to determine which areas require TSFAs. That is, these maps are not being used strategically to affect the planning process, but are only used as indicators of areas requiring detailed assessment.

8. What is the quality of the TSFA reports?

Assessing the quality of a geological report is subjective and difficult to do. We relied on the *Mapping and Assessing Terrain Stability Guidebook* (MOF) and the *Guidelines for Terrain Stability Field Assessments in the Forest Sector* (APEGBC) to outline the required elements of a TSFA report. These sources were used to identify the following criteria for assessing the TSFAs (Table 7).

Table 7: Criteria used for assessing TSFAs

Criteria	% of TSFAs
1. Historical landslide activity in adjacent cutblocks and roads is described.	10%
2. The existing landslide hazard within the proposed cutblock is described.	100%
A. Cutblock has been mapped into stratum (precise location descriptions or shown on a map) for assessment. Stability assessments are specific to each stratum.	68%
B. Landslide hazards in areas adjacent to or connected to the cutblock are described.	40%
3. Hazard and risk assessments are made for the proposed development of any area with a greater than low likelihood of landslides.	65%
A. The number, size and consequence of landslides are predicted.	30%
B. Road stability hazards are stratified by survey station.	64%
4. Recommendations are made to reduce and/or manage the landslide hazards and risks.	78%
5. Recommendations for water management along roads are made.	45%

The percentage figures in the table reflect the number of TSFAs that met each criterion in the three study areas combined. The provision of a general hazard rating for the entire cutblock was the only criteria met by all TSFAs. Stratification of the cutblock, with specific hazard ratings for each stratum, was done in 68 percent of the TSFAs. Risk ratings, which describe the expected consequence of a landslide, were present in 65 percent of the TSFAs reviewed. Risk assessment was more common in the most recently completed TSFAs. Only 10 percent of TSFAs met all five of these criteria. Criteria 1 and 5, in particular, were not met by most TSFAs. The lack of stratification of cutblocks for specific landslide hazards in 32 percent of the TSFAs is a significant shortcoming, as it limits the usefulness of TSFAs to forest managers.

We conclude from this short analysis that many TSFAs did not totally meet all the practices standards described in the government or professional association guidebooks. TSFAs completed more recently were generally of a higher standard than early reports. While the professional association guidebook was published after most of these TSFAs were written, the guidebook described current best practices at the time the TSFAs were written.

9. Do TSFAs provide an accurate assessment of terrain stability?

The conclusions of the TSFAs were examined to test how accurately the assessments predict the slope stability of a cutblock. We only examined cutblocks where landslides occurred; we did not look at the predictions of TSFAs on cutblocks that did not have landslides.

Using the criteria in Table 7, the TSFAs were categorized into one of three possible types:

Type 1: Hazard (for example, moderate likelihood of landslides) or hazard complex (low with some moderate) is identified. No map or description of exactly where the potentially unstable terrain occurs. No description of size of expected landslides, number of landslides, runout distances, potential effects or consequence.

Type 2: Hazard identified. Map or precise description of where unstable or potentially unstable sections occur. No information on frequency, magnitude or runout distance of expected landslides. Recommendations made to control landslide hazard.

Type 3: Hazard and risk identified. Map or precise description of high hazard areas. Description of expected size and frequency of landslides, consequence of landslides, and risk to other resources specified. Recommendations made to control landslide hazard.

There were relatively equal numbers of each type of TSFA made for the cutblocks that eventually had a landslide (Table 8). Type 3 assessments were the least common; only 10 of the 46 cutblocks had Type 3 assessments completed.

The stability prediction assigned to each cutblock was the highest hazard rating given to any portion of the cutblock. Also, the stability predictions for road stability and harvest stability are grouped; if separate stability predictions were made for roads and for harvesting, then the highest hazard rating was assigned to the cutblock. Not considered in this analysis were areas with a high likelihood of landslides that were excluded from the cutblock by the terrain specialist or forester.

Table 8: Stability predictions of TSFAs for cutblocks that had a landslide at a later date

TSFA Type	% of TSFAs that rated cutblock* as a High hazard	% of TSFAs that rated cutblock* as a Moderate hazard	% of TSFAs that rated cutblock* as a Low hazard
Type 1	16	75	9
Type 2	17	70	13
Type 3	25	67	8
Average	**18**	**71**	**10**

* only cutblocks that had a landslide were considered

All of the TSFA types were fairly consistent in predicting landslides in the cutblocks when assigning a moderate or high likelihood of post-logging landslide activity. Very few of these TSFAs stated that the likelihood of landslides was low (8-13 percent). About 20 percent of the TSFAs rated portions of the cutblocks that later failed as having a high likelihood of a landslide, however. Most of the areas that experienced landslides were rated as having a moderate likelihood of landslides.

Interestingly, the more general the assessment of hazard (e.g., Type 1) the higher the likelihood of an incorrect prediction. The detailed assessments (Type 3) had the best record of predicting a landslide occurrence.

A number of assessments identified the area as having a moderate or high likelihood of landslides, but went on to state that if "road construction was carried out as prescribed in the TSFA, that the residual likelihood of landslides will be reduced to low." Road-related landslides subsequently occurred in six of these cutblocks. A similar count was not made in the population of cutblocks that did not experience landslides, so a test of the reliability of such advice was not possible.

10. Why are landslides occurring in cutblocks where a TSFA was completed?

Some of the factors that may have contributed to the landslides observed in the study areas are listed in Table 9. This list contains only those factors that could be discerned from review of the TSFAs and the airphotos and has not been verified on the ground.

Table 9 : Contributing factors to landslides

Factor	% of Landslides
TSFA failed to identify unstable area	10%
TSFA identified likelihood of landslides, but predicted harvest would not increase the likelihood of a landslide occurrence	6%
Harvested area includes areas with a high likelihood of landslides	24%
Windthrow in adjacent unstable area	12%
Roads on an area with a high likelihood of landslides (unknown if prescribed measures implemented)	13%
No apparent reason	55%

*note: total is more than 100% as some cutblocks had two landslides

The conclusion from this analysis is that the TSFA conclusions and recommendations are not always being considered in cutblock design (i.e., harvesting of identified high hazard sites). This ties in with the earlier conclusion that about half of the silviculture prescriptions made no reference to the results of the TSFA. Alternatively, decisions are being made to harvest areas where landslides are expected but where the consequences are considered acceptable. Similarly, the recommendations for roads are either not being implemented, or are implemented but are not effective. In other cases, unanticipated problems, for example drainage diversions, are occurring that are affecting stability. Also, the adjacent forested areas that are subject to windthrow are affecting stability, and this factor is generally not being considered in most TSFAs, nor being accounted for in SPs—it is falling between the cracks.

Managing Landslides Under FRPA

Management of landslide-prone terrain in forest operations has evolved over the past 30 years in BC. In the early 1970s, there was little understanding of landslide processes and no regulatory requirement for terrain stability field assessments. In the 1980s, the *Coastal Fisheries/Forestry Guidelines* were introduced, which provided voluntary guidance on logging in environmentally sensitive areas. Then, in 1995, the Forest Practices Code was brought into force.

The Forest Practices Code set a high standard with its mandatory requirements for professional terrain stability mapping, assessments and prescriptions when harvesting on or near steep slopes. Furthermore, a Code guidebook (*Mapping and Assessing Terrain Stability*) specified the procedures for carrying out TSFAs. Government approval was required for any construction, modification or deactivation of roads on unstable slopes, and harvesting was not allowed in community watersheds on areas identified as unstable. The Code attempted to minimize the likelihood of occurrence of landslides, regardless of their potential consequence. The results from this investigation show that, so far, procedures carried out under the Code appear to have been effective in reducing landslides.

Under the new *Forest and Range Practices Act*, the low tolerance for landslides continues. The requirement is found in section 37:

> 37. Without unduly affecting the timber supply, an authorized person [e.g., a licensee] who carries out a primary forest activity [e.g., logging or road-building] must ensure that the primary forest activity does not cause a landslide that has a material adverse effect on a matter referred to in section 149(1) of the Act.

Section 149(1) refers to the following FRPA values:

- soils
- visual quality
- timber
- forage and associated plant communities
- water
- fish
- wildlife
- biodiversity
- recreation resources
- resource features
- cultural heritage resources

FRPA does not regulate impacts to human life, private property, and utilities, which are often the most serious consequences of a landslide.

Under FRPA, a licensee is not required to submit road designs for approval, complete TSFAs for harvest areas, or hire qualified registered professionals to make these assessments. A licensee will have flexibility and responsibility for deciding who to consult and what assessments to complete. That change will shift responsibility and accountability from government to licensees.

For a licensee, ensuring that forest practices did not cause a landslide is not the same as not causing a landslide. If no steps are taken to prevent landslides, it is possible that no landslide will occur—but a licensee can only "make certain" that a landslide will be avoided by taking reasonable care in their forest practices. So "ensure" in section 37 can be interpreted as requiring some kind of management system so that landslides do not result from forest practices.

Establishing a causal link between forest practices and a landslide is a complex undertaking. This will likely be an ongoing issue in future enforcement actions under FRPA, more than it was under the Code, because of FRPA's reduced reliance on approved plans. Under the Code, if a licensee failed to follow an approved road layout and design or silviculture prescription and a landslide occurred, government could take enforcement action based on the failure to follow the plan—a contravention under the Code. Under the Code, the government didn't necessarily have to establish the cause of the landslide, but under FRPA, government will always have to prove that the forest practices caused the landslide. Normally, however, it is extremely unlikely that one specific cause of a particular landslide can be clearly defined, although it may be possible to identify the trigger.

The final element of section 37 is the "material adverse effect" on FRPA values. Now the focus of steep slope management is on landslide risk, rather than hazard. Under FRPA, the consequence of the landslide has more clearly entered the equation. Those responsible for forest development will now have to apply landslide risk management within a decision-making framework, to adequately balance environmental and timber supply objectives. The results of a TSFA regarding the probability of a landslide (and its likely consequence) must be clearly stated, so that forest resource managers can make sound decisions on acceptable risk.

With the new reliance on professionals to prevent landslides that have a material adverse effect, professional associations should clearly define the responsibilities of their members when conducting assessments. Many of the assessments reviewed in this study do not provide the necessary information to conduct a landslide risk assessment. APEGBC must ensure its members follow a high standard of practice when preparing assessments, particularly when operating in challenging terrain. APEGBC has recently provided such guidance to its members through the *Guidelines for Terrain Stability Field Assessments in the Forest Sector*, and the Board encourages this type of support for professionals.

One might ask why licensees would conduct terrain assessments under FRPA if not required to by legislation. There are good reasons why licensees might continue to do so:

- First, to be seen as good corporate citizens. They are likely to have environmental management systems that require terrain assessments in order to maintain independent third-party certification or to achieve a clean audit from the Forest Practices Board.

- Second, to avoid civil liability. The civil law and workers compensation legislation are the main legal mechanisms for enforcing this responsibility.

- Third, to avoid administrative penalties or court fines that may be imposed if a landslide with a material adverse effect occurs. A licensee must ensure that the standard of care applied is appropriate for the conditions encountered, particularly if it wishes to demonstrate due diligence as a defense.

These points aside, both the shift to licensee-driven decision-making in steep-slope management, and the shift from hazard-based to risk-based management, are significant changes from what existed under the Code. There will undoubtedly be a range of responses from licensees to this new challenge. Only time will tell; but in this case, the time is 10-15 years of harvesting before the outcome is known.

CSA's *Risk Management: Guidelines for Decision Makers* (1997) says it well:

> The objective of risk management is to ensure risks are identified and that appropriate action is taken to minimize these risks as much as is reasonably achievable. Such actions are determined based on a balance of risk control strategies, their effectiveness and cost, and the needs, issues, and concerns of stakeholders.

Conclusions

The Board has examined the management of landslide-prone cutblocks through evaluation of terrain stability mapping and terrain stability assessments for three areas in BC. While the results of this survey must be considered preliminary, because of the extended time scale over which landslides can occur, the following conclusions can be made:

- Landslides were significantly reduced after the Code came into effect in 1995. However forestry-related landslides are still occurring. In three areas representative of landslide-prone terrain on the Coast and in the Interior, Code road and harvest-related landslides over the past 10 years average one landslide for every 12 steep slope cutblocks or one landslide for every 14 square kilometres of steep slope cutblock each year. While these numbers are low, they represent an increase over the rate of natural landslide activity.

- Roads constructed prior to the Code coming into effect are continuing to fail, in spite of considerable road deactivation work.

- There is a significant probability that any landslide that does occur will have an environmental effect. Approximately 60 percent of the Code landslides may have had a "material adverse effect on a forest value," using the Board's criteria.

- Code landslides differ from pre-Code landslides. Code landslides are much less frequent in gullies, along stream escarpments and off roads compared to pre-Code cutblocks.

This probably reflects the retention of reserves and management zones around streams and gullies, as well as better road location and construction methods under the Code.

- Landslides are not a significant soil conservation issue, at the landscape level, disturbing only 0.3 percent of the total cutblock area. Landslides can still be a soil conservation issue at the individual cutblock scale.

- Road deactivation appears to effectively stabilize Code roads. However, deactivation of some pre-Code roads has not fully restored hillslope stability; a significant number of landslides have occurred along deactivated pre-Code roads.

- The factors that contributed to the landslides are difficult to determine; over half could not be determined. Of the remainder, harvesting and road building on identified high hazard areas, or of windthrow in adjacent areas, are the most common contributing factors.

- Reconnaissance terrain stability mapping, prepared by professional geoscientists, correctly identified most cutblock areas that eventually experienced landslides, as potentially unstable or unstable. No landslides occurred in cutblocks mapped as stable. Reconnaissance terrain stability mapping did not appear to be used strategically in planning the location of cutblocks and roads, but rather it is used mainly for determining where a terrain stability field assessment is needed.

- Terrain stability field assessments (TSFAs) were carried out on 92 percent of the cutblocks where they were legally required. There were three cases of significant non-compliance where cutblocks did not have a TSFA, and later experienced a landslide. The results of a TSFA were not always incorporated into the SP, as is required. About 40 percent of SPs do not address the results of the TSFA. The TSFA conclusions and recommendations were also not always being considered in cutblock design (i.e., harvesting of identified high hazard sites). Similarly, the recommendations for roads were not always implemented, were implemented but were not effective, or unanticipated problems (e.g., drainage) occurred and affected stability. Also, the adjacent forested areas that are subject to windthrow affected stability and this factor is generally not being considered in most TSFAs, and is not being accounted for in SPs—it is falling between the cracks.

- The comprehensiveness of TSFAs was quite variable. All TSFAs provided an estimate of the likelihood of a landslide occurrence for the cutblock. Overall, the TSFAs consistently predicted a moderate or high likelihood of a landslide in cutblocks that later failed. However, a number did not stratify the block by hazard class; provide hazard assessments for adjacent areas; or estimate the size, the number or the consequence of the landslides. Most TSFAs did provide recommendations to reduce landslide hazard. The more recent TSFAs were generally the most comprehensive.

- The challenge for landslide management under FRPA is to maintain and improve on the gains made during the Code. Licensees will have the discretion on when and where to conduct mapping and assessments. Another shift, from a hazard prevention strategy to a risk management system, is a significant change from what existed under the Code. That is, the consequence of landslides has now entered the equation and forest managers will have to apply landslide risk management to balance environmental and timber supply objectives.

Recommendations

In accordance with section 131 of FRPA, the Board makes the following recommendations:

1. The landslide management system that was developed under the Code should continue under FRPA. Terrain stability field assessments can be a strong tool for management of unstable terrain. Licensees should continue doing terrain stability field assessments and use the results.

2. The Ministry of Forests and Range regional offices should establish quantitative criteria for classifying landslide hazard in terrain mapping. A landslide hazard class should be defined by the probability or expected frequency of landslides per unit area, rather than by a subjective description.

3. The Ministries of Forests and Range and Environment should establish what "a material adverse effect" from landslides would be for each resource value—with public resources it is the role of government, not individual licensees, to define where the threshold is for a material adverse effect on resource values. It is important to develop criteria for acceptable risk for each of the FRPA values separately.

4. The Ministry of Forests and Range should regularly conduct inventories of landslides as part of the Forest and Range Evaluation Program, as there is no FRPA requirement for licensees to report landslides.

5. Licensees should use a decision-making framework for the management of landslide risk. A framework separates the process of landslide risk management into distinct steps and clarifies the respective roles of terrain stability professionals and forest resource managers. (See the Board's Reiseter Creek complaint investigation for more discussion of this concept.) Licensees should also develop objective criteria for triggering when a TSFA must be conducted to provide consistency in application across their operations. One example is the criteria currently being developed by a coastal licensee that combines terrain stability mapping, climatic zone mapping and watershed use to trigger when a TSFA is needed.

6. The Joint Practices Board, or the ABCFP, should develop companion guidelines for forestry managers to the APEGBC *Guidelines for Terrain Stability Assessments in the Forest Sector*. This guidebook should provide advice to the forest manager in applying appropriate levels of landslide risk management. The guidebook should also provide standardized terminology for effective communication and clarify the responsibilities of forest managers and terrain professionals.

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APPENDIX 1

Use of Satellite Imagery for Landslide Mapping and Environmental Monitoring

The Board is continually seeking new tools for conducting audits or environmental auditing, particularly under the *Forest and Range Practices Act*. Advances in the resolution of satellite imagery present an opportunity for monitoring of soil disturbance, stream channel changes and change to forest structure. The frequency of recurring coverage (numerous times a year) offers some benefits over conventional airphoto coverage.

The utility of satellite imagery for landslide detection was evaluated by interpretation of orbital imagery (SPOT, IKONOS, and QUICKBIRD) and comparison with large- and medium-scale aerial photography. Satellite imagery was enhanced by simple, repeatable digital image processing techniques (contrast stretches and transformations, merging of images of different spatial resolutions, composition of 3-band composite images, and band ratioing). More numerous processing options were available for IKONOS and QUICKBIRD imagery than for SPOT, due to the multispectral nature of the former.

Approximations of the smallest landslides visible under ideal illumination and viewing conditions were 1700 m^2 (.17 ha) for 5 m SPOT panchromatic imagery, 1000 m^2 (0.1 ha) for 2.5 m SPOT panchromatic imagery, and 175 m^2 (.02 ha) for multispectral IKONOS and QUICKBIRD imagery. Insufficient perception of terrain morphology at these sizes, however, prevents absolute identification of the features as landslides. In the absence of stereo viewing, greater minimum landslide sizes than those indicated above for detection are required for landslide identification. The exact landslide size varies with illumination conditions, viewing geometry, and contrast between the landslide and the surrounding terrain. Topographic shadowing was found to hinder landslide interpretation on both aerial photographs and satellite imagery. This problem was severe for SPOT panchromatic imagery, but was slightly reduced by image contrast transformation. Shadow problems were significantly reduced on IKONOS and QUICKBIRD imagery by band ratioing using the red and near infrared bands.

One of the most important factors affecting the ability of a sensor to detect landslides is spatial resolution. All other conditions being equal, the minimum size of a feature detectable from remotely sensed imagery decreases as spatial resolution increases. As sensor resolution increases, however, the area covered by a single image decreases, reducing the coverage provided by the imagery.

Several conclusions are made:

- High spatial resolution, multi-spectral data collection, and stereoscopic viewing greatly improve the ability of a sensor for landslide detection.
- IKONOS and QUICKBIRD imagery out-performed SPOT imagery for landslide detection.

- The processed images allowing for optimal interpretation of IKONOS and QUICKBIRD scenes are colour infrared composites and band ratioed images.
- Despite multispectral imaging and high spatial resolution (relative to other satellites) IKONOS and QUICKBIRD did not allow delineation of all landslides visible on largescale aerial photographs.
- Increased aerial coverage provided by satellite images (relative to a single aerial photograph) improves ease of imagery assessment.

Recommendations for future evaluation of remotely sensed imagery for landslide detection are:

- Imagery used for landslide detection should combine three properties: high spatial resolution, multi-spectral data collection, and if possible, stereoscopic viewing.
- A multi-scale approach to landslide investigations using satellite imagery and aerial photography could be used.